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Land Use Effects on Atmospheric ^{13}C Imply a Sizable
Terrestrial CO_2 Sink in Tropical Latitudes.

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Records of atmospheric CO₂ and ¹³CO₂ can be used to distinguish terrestrial vs. oceanic exchanges of CO₂ with the atmosphere (1-3). However, this approach has proven difficult in the tropics, partly due to extensive land conversion from C₃ to C₄ vegetation (4). We estimated the effects of such conversion on biosphere-atmosphere ¹³C exchange for 1991 through 1999, and then explored how this "land-use disequilibrium" altered the partitioning of net atmospheric CO₂ exchanges between ocean and land using NOAA-CMDL data and a 2D, zonally averaged atmospheric transport model (5). Our results show sizable CO₂ uptake in C₃-dominated tropical regions in 7 of the 9 years; 1997 and 1998, which included a strong ENSO event, are near neutral. Since these fluxes include any deforestation source, our findings imply either that such sources are smaller than previously estimated, and/or the existence of a large terrestrial CO₂ sink in equatorial latitudes.

From an atmospheric perspective, the carbon cycle in tropical regions has long been perplexing. Data from terrestrial environments strongly suggest that high rates of land-use change are causing losses of CO₂ to the atmosphere; one recent estimate (5) suggested an average efflux in the 1980's of 2.0 Gt/yr, nearly all from the tropics. Oceanic pCO₂ data also suggest that the tropical oceans should be a net source of CO₂ to the atmosphere in most years (6,7). Thus, one might expect to see clear evidence of these sources in the tropical atmosphere, yet several studies (8-10) have suggested that the net fluxes of CO₂ from earth's equatorial regions may be smaller than predicted from the sum of deforestation and oceanic effluxes.

In part, our limited understanding of the carbon cycle in tropical regions may be due to the fact that isotopic techniques which allow estimates of how net C fluxes are partitioned between land and ocean face some unique hurdles in equatorial latitudes. These techniques have proven to be powerful tools in other regions, and take advantage of the facts that: 1) the product of carbon and its isotopic ratio is conservative in the atmosphere, and 2) photosynthesis on land discriminates strongly against ^{13}C , whereas the effects of oceanic exchange are comparatively small. The global atmospheric $^{13}\text{CO}_2$ budget can be expressed as:

$$\frac{d}{dt} C_a \delta_a = F_f \delta_f + N_s (\delta_a + \epsilon_{as}) + N_b (\delta_a + \epsilon_{ab}) + D_s + D_b \quad (1)$$

where C_a is the atmospheric pool of C, δ_a is its ^{13}C value (in ‰ relative to PDB), F_f is the fossil fuel release, δ_f is its ^{13}C value, N_s and N_b are net ocean and land exchanges of C with the atmosphere, and ϵ_{as} and ϵ_{ab} are the isotopic fractionation factors associated with air-sea transfer and photosynthesis, respectively, expressed as the small differences from 1 in per mil. The last two terms are isotopic disequilibria, defined as the product of the one-way gross flux and the average isotopic difference between reservoir-to-atmosphere fluxes and atmosphere-to-reservoir fluxes (11). The two disequilibria in equation 1 are non-zero due to historical changes in atmospheric $^{13}\text{CO}_2$. These changes cause today's uptake of CO_2 into land or ocean reservoirs to reflect today's atmospheric ^{13}C value, but effluxes of CO_2 from these reservoirs reflects the ^{13}C content of a historical atmosphere (11). It has been shown that such disequilibria can have a significant effect on isotopically-derived estimates of terrestrial vs. oceanic carbon fluxes (12).

The tropics present an additional problem not reflected in equation 1: widespread areas of vegetation containing the C_4 photosynthetic pathway. Unlike C_3 plants, C_4 vegetation displays only minor discrimination against ^{13}C during CO_2 uptake (13), and therefore fluxes of carbon between C_4 areas and the atmosphere cannot be readily

distinguished from those between ocean and atmosphere (3). Worse yet, most tropical deforestation occurs in C_3 forests, but the vast majority of vegetation that replaces these forests is C_4 pasture grasses or crops. This conversion causes respiration of soil carbon to be significantly lighter in ^{13}C than the newly formed plant material for several decades, in turn creating a net flux of ^{13}C from atmosphere to land (Fig. 1). This "land use disequilibrium" does not occur over spatial scales nearly as large as do those arising from historical changes in the atmosphere, but the isotopic change created by rapid C_3 to C_4 shifts can more than an order of magnitude greater than that from atmospheric change. While the potential importance of land use change on the atmospheric ^{13}C budget has been recognized in past studies (3, 14), attempts to use atmospheric $^{13}CO_2$ data to estimate land versus ocean carbon exchanges have not been able to account for this effect.

The land-use disequilibrium can be written as:

$$D_{lu} = R_{lu}(\delta_{resp} - \delta_{assim}) \quad (2)$$

where R_{lu} is heterotrophic respiration from lands which have been converted from C_3 forest to C_4 crops or pasture, δ_{resp} is the ^{13}C value of that flux, and δ_{assim} is the ^{13}C value of the new C_4 vegetation. In theory, D_{lu} can be added easily to equation 1, but estimating its value requires knowledge about the heterotrophic respiration and the isotopic imbalance of every parcel of cleared land which has a disequilibrium created by a change from C_3 forest to C_4 pasture or crops.

Following such a change, the soil carbon pool will continue to respire C_3 carbon, but the fraction of heterotrophic respiration which is C_3 will decline (Fig. 1), and frequently, the total respiration flux will also decline as land is degraded (15). Thus, a recently cleared pasture will have a much greater D_{lu} than an old pasture. A single, global D_{lu} value for a given year must therefore account for the age of every piece of converted land that contributes to this value:

$$D_{lu} = \sum_{i=1}^n G_i(\delta_{assim} - \delta_{resp})i \quad (3)$$

where i through n represent annual age classes of cleared lands.

Our estimate of D_{lu} focused on land conversion in moist tropical forests. Most of the annual conversion rates were taken from two published sources (16,17); the exception was for recent rates of conversion in the Amazon basin, where we used data from the Brazilian agency INPE (18). The conversion rates represent net changes in forest area (from forest to pasture or agriculture). We compiled single average values for Latin America, Africa and Asia for every year beginning in 1950. Not all years and continents have annual data, especially prior to the 1980's, therefore decadal averages were used for many of the early numbers. Most (but not all) converted land in Latin America and Africa is either pasture or C_4 crops (19, 20); we assumed that 80% of the total conversion was a C_3 - C_4 change. Due to widespread rice cultivation in Asia, we assumed a value of 50% in this region.

We used Century model (21) simulations of selected sites in all three continents to estimate the amount and ^{13}C value of respired C in the decades following conversion (fig. 1); isotopic values for C_3 and C_4 vegetation were set at -27 and -13‰, respectively. These simulations generated estimates of D_{lu} on a per area basis at any given time since conversion; the conversion data referenced above were then used to derive a pan-tropical value in any given year. Century simulations were validated against data from pasture chronosequences in Costa Rica, Brazil and Hawaii; in all cases the model was able to predict isotopic changes over time with reasonable accuracy (e.g. Fig. 1). We wish to note that while uncertainties remain in our ability to model soil carbon turnover in tropical systems, predictions of the time course of isotopic change following vegetation shifts are subject to much less uncertainty than is the land-use data itself.

As can be seen in figure 1, differences between the isotopic values of photosynthetic vs. respiration fluxes persist for decades, even in these warm climates. Thus, a pasture formed forty years ago can still contribute to D_{lu} . However, by far the greatest isotopic imbalance is found in the first few years following conversion, therefore recently cleared areas dominate the D_{lu} value for any given year. This is fortunate for our estimates, in that data on rates of land conversion are far better constrained in recent years than they are for earlier decades.

One significant uncertainty in deriving D_{lu} estimates lies in the fact that older cleared lands are often abandoned and begin to undergo secondary succession of C_3 vegetation (22). The clearing rates we used represent net losses in forest area, but cleared, abandoned land will not show up in these data as forest until it has undergone significant succession. Thus, some of the cleared area in our estimates will be land that is an uncertain mix of C_3 and C_4 vegetation. Potentially, this switch from C_4 back to C_3 could help offset the size of D_{lu} by creating lands with an isotopic imbalance opposite in sign to that of the original clearing. However, unlike the original clearing where the change from C_3 to C_4 is rapid, secondary succession replaces C_4 with C_3 vegetation at a slower rate. The time scale of this change also depends on the age of the abandoned land (23). For example, in older cleared areas, the $\delta^{13}C$ signature of soil carbon will have significantly changed from a C_3 value to one close to that of the C_4 vegetation, creating the potential for a large disequilibrium in the reverse direction. However, succession into these older areas tends to be very slow, occurring on roughly the same time scales as soil carbon turnover (23, 24). In contrast, cleared lands abandoned in the first few years after conversion will return quickly to nearly all C_3 vegetation, but their soil carbon will also have relatively little C_4 carbon prior to abandonment. The net result in either case is that any imbalance due to secondary succession is likely to be small relative to the effects of the initial conversion.

We therefore assumed that secondary succession in abandoned pastures or croplands probably does not create a large isotopic disequilibrium, but once land is abandoned, that land's contribution to D_{lu} probably ceases. Thus, although there are very old parcels of cleared land in tropical regions that still contribute to D_{lu} , others have been abandoned much more rapidly. This fact requires that we make some assumptions about how far back into the clearing record we should include lands as contributing to the total disequilibrium. As a sensitivity test, we calculated several values that span a range from only the most recent 10 years of clearing up to 40 years. These values throughout the 1990's are shown in figure 2, and several important attributes of the land-use disequilibrium are apparent from this figure. First, because younger cleared sites have by far the greatest isotopic imbalance (Fig. 1), the contribution to the total D_{lu} value is much greater from the most recent 10 years of clearing than from prior decades. Most of the difference between the 10 and 20 year lines in figure 2 is due to the much larger isotopic imbalance in recently cleared lands rather than to any substantive difference in clearing rates between decades. Second, figure 2 shows that assuming average ages of abandonment in excess of 20 years makes a relatively minor difference in the total D_{lu} value.

We then took the values for D_{lu} based on a range of average abandonment times from 10 to 40 years and assessed their effect on the partitioning of regional-scale, surface-atmosphere carbon exchanges between land and ocean reservoirs. Briefly, the estimates of carbon exchanges by latitude are derived as follows. For every year since 1990, the Stable Isotope Laboratory at INSTAAR has measured $\delta^{13}C$ values of CO_2 in weekly samples of air taken from a global network of sites; these isotopic data complement NOAA/CMDL's measurement of CO_2 mixing ratios from these sites (25). The smoothed data are then used to estimate the latitudinal distribution of net surface fluxes of CO_2 and $^{13}CO_2$ via inverse application of a two-dimensional atmospheric

transport model (14,26). Finally, the separation of net fluxes into land and ocean components is done using linear equations (similar to eq. 1 above) in which the known fossil fuel contribution is removed, and the various isotopic fractionation factors and disequilibria are specified. Full descriptions of the data and modeling techniques used here can be found elsewhere (5,12).

Figure 3a shows the effects of adding the 20 year land use disequilibrium values to the estimates of land vs. ocean fluxes in tropical latitudes (17°N-S; the effects in higher latitudes are minor). Incorporation of D_{lu} into this analysis alters the partitioning of fluxes by an average of 1.04 Gt per year over the 1990's; the direction of this change is for greater carbon uptake by C_3 ecosystems. Two striking features emerge from figure 3. First, despite abundant evidence that land use change in C_3 regions of the tropics is responsible for large losses of C to the atmosphere, these regions display net uptake of CO_2 for 7 of the 9 years in the record. The remaining two years, which span a strong ENSO event, are near neutral. This suggests the existence of a sizable terrestrial sink for atmospheric CO_2 in tropical forests, one that in some years may rival that estimated for mid-latitudes of the northern hemisphere. Several other recent approaches to understanding the carbon balance of the terrestrial tropics, ranging from flux tower measurements (27), to forest inventories (28), to ecosystem modeling (29), have also suggested the possibility of a sizable C sink. The mechanisms behind such a sink are unknown, though areas of regrowth (30), rising CO_2 levels (31) and climatic variability (32) have all been proposed as possibilities. Furthermore, exchanges of CO_2 between tropical forests and the atmosphere are higher than for any other biome, therefore a small percentage deviation from equilibrium in photosynthetic and respiration fluxes can still have a significant impact on the atmosphere (33).

Second, the blue line in figure 3a shows the net flux for oceans *and* lands dominated by C_4 vegetation; these cannot be separated in this analysis. Our results

suggest that when the land use effect is considered, the majority of the net efflux of CO_2 from the earth's surface to the atmosphere in tropical latitudes is due to net losses from oceanic or C_4 vegetation realms. This result is consistent with oceanic pCO_2 data, and is also consistent with the fact that C_4 dominated lands are subjected to heavy anthropogenic use throughout the tropics, use which frequently leads to degradation and net C losses (4).

The values in figure 3a assume a 20 year contribution of cleared lands to the land use disequilibrium; figure 3b shows the net flux from C_3 lands using a range of D_{lu} values from 10 to 40 year abandonment times, as well as the net flux assuming no land use effect. It is entirely possible that the 20 year value is an overestimate. However, for several reasons we believe that this value is unlikely to represent a large deviation from reality. First, we assumed that only 80% of clearing in Latin America and Africa represented a C_3 - C_4 shift, and that only half did so in Asia; this is quite possibly an underestimate. For example, several studies have shown that nearly all forests cleared in the Amazon are converted to areas of C_4 vegetation (19). Second, as noted above, D_{lu} is dominated by the contribution of more recently cleared lands; as an example, cutting the 20 year value in half only reduces D_{lu} by 30%. Third, even if our chosen value for D_{lu} is somewhat high, the value is growing every year as more land is cleared, unless average abandonment times for cleared lands are decreasing. Finally, and perhaps most importantly, the implication that a significant terrestrial sink exists in tropical forest regions – and/or of much smaller values for deforestation losses than typically assumed – would remain even if we used a D_{lu} value that only accounted for the last 10 years of clearing (figure 3b).

The difficulties of quantifying C_3 - C_4 conversion areas and their average time until abandonment at a pan-tropical scale unquestionably introduce error into any estimate of D_{lu} . For example, although we assumed C_3 - C_4 conversions represented a complete

change in photosynthetic pathways, most tropical pastures do contain some C₃ woody vegetation at nearly any age. In part, this is why we attempted to use conservative values for the fraction of all deforestation that is a C₃-C₄ change. Moreover, we recognize that inverse modeling results are most uncertain in the tropics due to vigorous vertical mixing in the equatorial atmosphere. However, we believe the range of values shown in figure 3b makes it clear that the isotopic imbalance created by such land use change is large enough to require its incorporation into any estimate of tropical carbon fluxes that is based upon atmospheric ¹³C data. Tropical ecosystems cycle more carbon annually than any others on earth, and thus have the greatest potential to affect atmospheric CO₂ levels at decadal time scales. Given the rapid land use and economic changes occurring in the tropics, it is essential that we understand not only the current effects of tropical ecosystems on atmospheric CO₂, but also the mechanisms that drive these effects so that we may have some predictive power for the future.

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Figure Legends

Figure 1. ^{13}C values for heterotrophic respiration following a change from C_3 forest to C_4 pasture. Data are from a pasture chronosequence in Costa Rica; solid line shows the results of a Century model (21) simulation for the same sites.

Figure 2. Values for the land use disequilibrium (D_{lu} ; see equations 2 and 3) throughout the 1990's assuming different average ages of abandonment for cleared lands. For example, the 10 year line assumes that only land cleared in the ten years prior to the year for which the value is shown contributes to that value, and that all cleared land older than ten years is isotopically in balance. The lines are as follows: 10 yr – circles; 20 yr – squares; 30 yr – diamonds; 40 yr – triangles. Units are in Gt C per mil.

Figure 3. (a) 1991-2000 smoothed (one year) net CO_2 fluxes between earth's surface and the atmosphere between 17°S and 17°N (red line) without the contribution of fossil fuel emissions, and the separation of those fluxes into C_3 land (green line) and ocean plus C_4 land (blue line) components. This separation incorporates the 20 year values for D_{lu} (see figure 2). Positive values represent a net flux to the atmosphere; negative values are net uptake. Units are 10^{14} mol CO_2 per year.

(b) Net annual CO_2 fluxes between C_3 lands and the tropical atmosphere (17°N-S) assuming no land use disequilibrium (black dashed line), D_{lu} values assuming 10, 20 and 30 year abandonment times (red, blue and green lines, respectively), and a "maximum possible" value in which a 40 year abandonment time is used and all land conversion is assumed to be C_3 to C_4 (purple line).

Figure 1

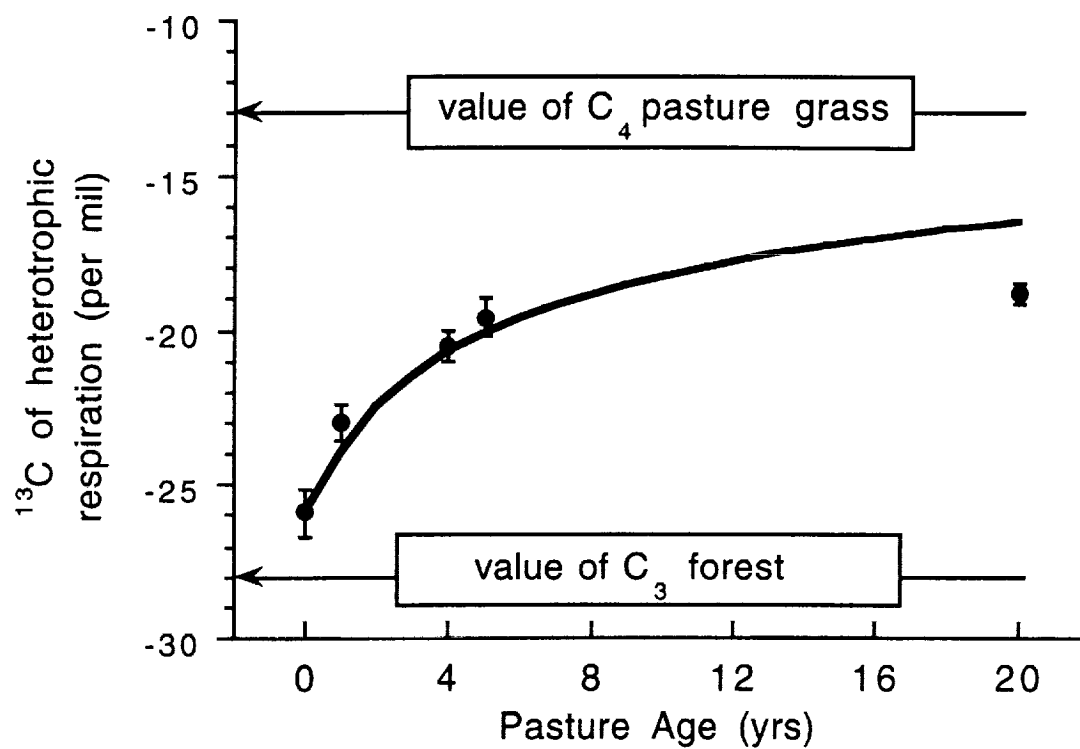


Figure 2

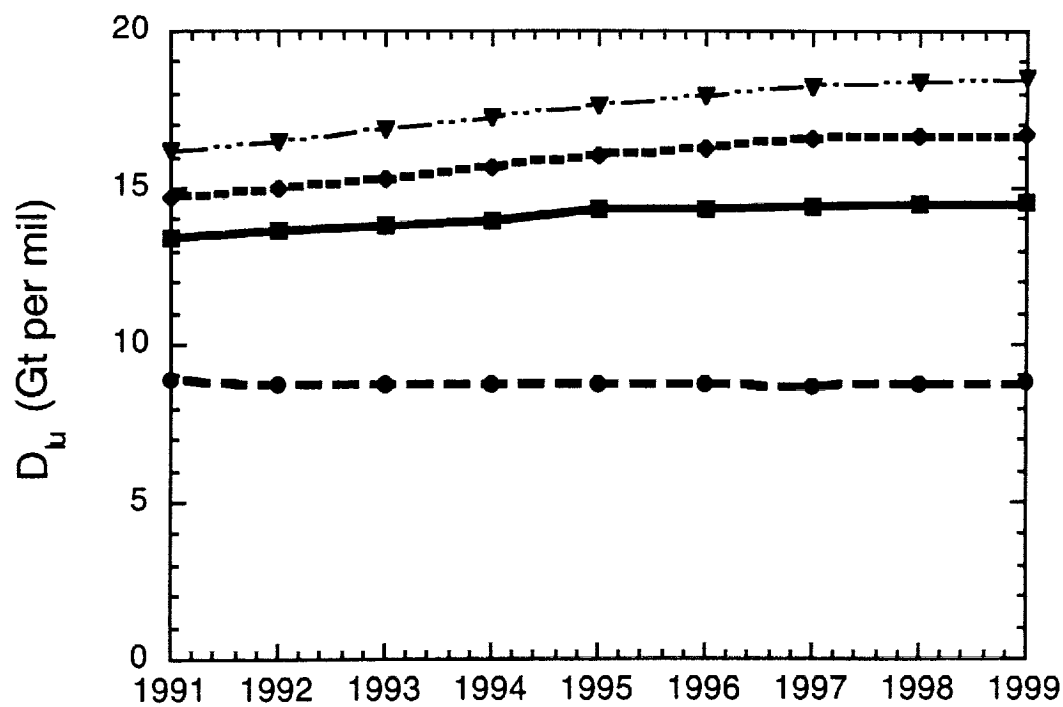


Figure 3a

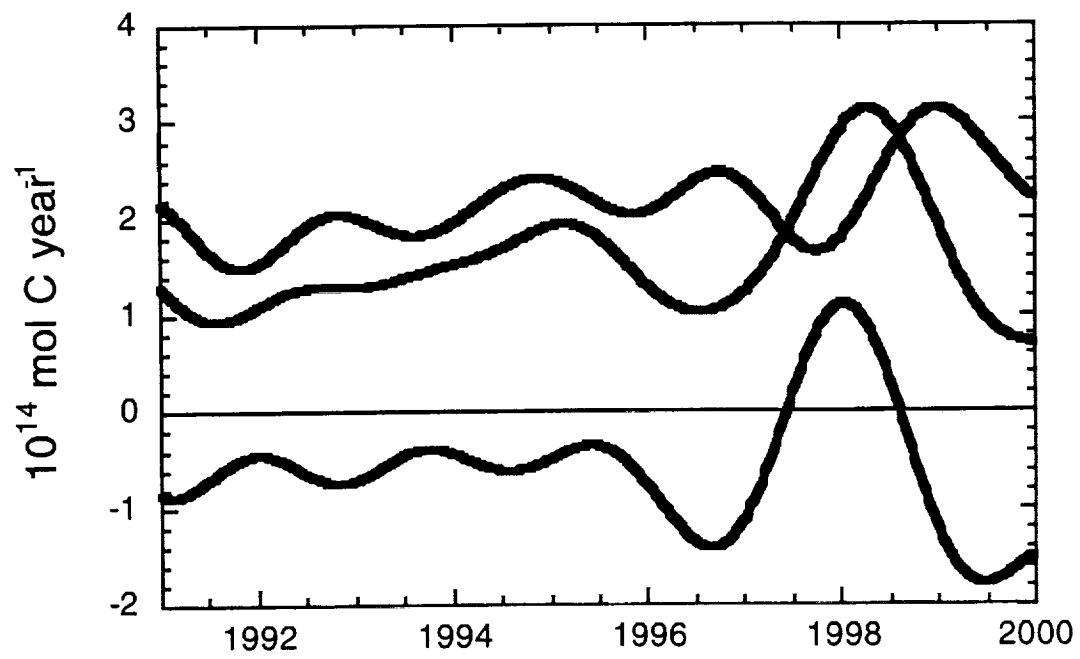


Figure 3b

